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Approaches to Robotics in the United States and Japan

Report of a Bilateral Exchange

NATIONAL RESEARCH COUNCIL

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Approaches to Robotics in the United States and Japan: Report of a Bilateral Exchange

Office of Japan Affairs
Office of International Affairs
National Research Council

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Since 1985 the National Academy of Sciences and the National Academy of Engineering have engaged in a series of high-level discussions on advanced technology and the international environment with a counterpart group of Japanese scientists, engineers, and industrialists. One outcome of these discussions was a deepened understanding of the importance of promoting a more balanced two-way flow of people and information between the research and development systems in the two countries. Another result was a broader recognition of the need to address the science and technology policy issues increasingly central to a changing U.S.-Japan relationship. In 1987 the National Research Council, the operating arm of both the National Academy of Sciences and the National Academy of Engineering, authorized first-year funding for a new Office of Japan Affairs (OJA). This newest program element of the Office of International Affairs was formally established in the spring of 1988.

The primary objectives of OJA are to provide a resource to the Academy complex and the broader U.S. science and engineering communities for information on Japanese science and technology, to promote better working relationships between the technical communities in the two countries by developing a process of deepened dialogue on issues of mutual concern, and to address policy issues surrounding a changing U.S.-Japan science and technology relationship.

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BILATERAL EXCHANGE ON APPROACHES TO ROBOTICS IN THE UNITED STATES AND JAPAN

Tokyo, Japan
September 27-29, 1989

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Adept Technology, Inc.

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Transitions Research Corporation

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Boston University

RAMCHANDRAN JAIKUMAR,
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SRI International

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RUSSELL TAYLOR,
IBM Watson Research Center

DONALD VINCENT,
Robotics Industry Association

WILLIAM WHITTAKER,
Carnegie-Mellon University

Japanese Participants

RYOICHI NAKAGAWA,
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JUNICHI BABA,
Mitsubishi Electric Company

YUKIO HASEGAWA,
Waseda University

OSAMU HAYAMA,
Nomura Research Institute

HAJIMU INABA,
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ICHIRO KATO,
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SHUN KINOSHITA,
Agency of Industrial Science and Technology

TSUNEO NAKAHARA,
Sumitomo Electric Industries

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Agency of Industrial Science and Technology

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KENJI USHITANI,
Toyota Motor Coporation

TSUNEJI YADA,
Mechanical Engineering Laboratory

KANJI YONEMOTO,
Japan Industrial Robot Association

Preface

The Bilateral Exchange on Approaches to Robotics in the United States and Japan was a direct outgrowth of earlier high-level discussions between the National Academies of Science and Engineering in the United States and the Japan Society for the Promotion of Science. Those discussions, on "Advanced Technology and the International Environment," led to a recognition of differences, or asymmetries, in the organization of R&D systems in the United States and Japan—structural differences that must be overcome if both countries are to benefit from scientific and technological exchange. Robotics was selected as a topic for more focused discussion by experts from the two countries.

The Office of Japan Affairs and the Manufacturing Studies Board of the National Research Council cooperated in this effort. A committee of U.S. experts from business and academe, chaired by John McTague of Ford Motor Company, was selected. Months of preparation by and consultation between the two countries laid the foundation for the meeting held in Tokyo, September 27-29, 1989. Two days of formal discussion between U.S. and Japanese experts culminated in an open forum in which the results of the meeting were summarized and views exchanged with members of the newly established Engineering Academy of Japan. On the third day of the meeting the Japanese committee hosted the U.S. committee on site visits to corporate R&D facilities engaged in robotics work.

This report highlights major themes from the discussion. It is not a conference proceedings or a consensus document. Its purpose is to convey a sense of the discussion around a major topic of the U.S.-Japan meeting—cooperation, where and when it makes sense, between the United States and Japan in robotics R&D.

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Executive Summary

The increasing globalization of industry in developed countries is rendering international collaboration more desirable from both economic and technological perspectives. Robotics technology, in particular, is at a crossroads. Growing consumer demand for individualized products is forcing many manufacturers to shift to smaller production runs of greater varieties of products, a move that relies on highly flexible factory automation systems; for robots this means higher-level intelligence. Further development of robotics technology holds the promise of robots capable of working in less structured environments—outdoors and in the home.

The advances in sensing and control technology as well as mechanisms needed to realize the next generation of robots will rely on programs of basic research too extensive for any one company or institution to fund. Major gaps in sensing include cost-effective range sensors for constructing three-dimensional range maps, vision systems capable of interpreting three-dimensional scenes, and tactile sensors capable of detecting both patterns and force distributions. Needed in the area of control are geometric reasoning and control software; techniques for acquiring process and environmental knowledge; and significant developments in navigation, control of flexible structures, and control of forces rather than position. Greater understanding of neural networks as applied to control also is needed. In terms of the mechanisms that will be required, lighter-weight actuators and improved transmissions, particularly variable-ratio transmissions, will be essential.

Research has been under way in many of these areas for more than 20 years; to make real headway, it may well require an effort on the order of that for the space program. In theory, U.S.-Japanese collaboration could both fill the technology gaps identified above and yield important cultural benefits in the form of knowledge of how to better set up and manage collaboration within our respective economies and improved understanding of each other's R&D systems.

The history of U.S.-Japanese collaboration in robotics, however, has left many U.S. firms skeptical. Because of this, any attempt to identify appropriate areas for joint research must consider the difficult questions of how to ensure that both U.S. and Japanese companies are afforded equal opportunity to turn the research into products and what mechanisms might be devised to afford U.S. companies the same access to Japanese markets as Japanese firms have to U.S. markets.

Several Japanese initiatives are in place. Japan is promoting international collaboration through the Symposium for International Cooperation on Industrial Robots, the International Robotics and Factory Automation Center, the International Joint Research Development Program for Next Generation Production Technology, and the Law for Facilitating Governmental Research Exchange. A Japanese proposal for an international project, Intelligent Manufacturing System, was under discussion in early 1990. The United States, for its part, faces significant challenges in securing needed cooperation among various funding agencies and making non-defense-related funding available.

Several criteria have been advanced for identifying mutually attractive areas of cooperation. Projects in areas without prospects for immediate commercialization are appropriate for consideration as first steps; the benefits of collaboration should be clear to both sides (neither should have a commanding position; capabilities should be complementary); and projects should produce concrete outputs in a relatively short (1- to 3-year) period of time.

Several areas of collaboration that might yield projects that meet these criteria have been identified. Both Japanese and U.S. policymakers are interested in nuclear emergency and disaster response technologies, which are still in their infancies. Needs in these areas include radiation-hardened electronics and autonomous locomotion in human-scale spaces. Robotic applications in health care, another area of potential collaboration, will rely on the development of polaroid range sensors and require greater reliability and precision than have heretofore been achieved. Collaboration could also be aimed at assessing the socioeconomic impacts, for example, of man-machine interactions. Potential subjects might include future-oriented issues, such as comparative views of investment, training, and laboratory-to-factory technology transfer required by corporations doing business around the world. New approaches needed by both countries for training and retraining managers and workers in the rationale for and use of robotics, automation, quality programs, value engineering, and computer technology constitute an area of potential collaboration.

This report relates past experience, suggests areas of cooperative effort and criteria for evaluation, and discusses existing and needed frameworks for supporting collaborative efforts. It will be the challenge of the governments and industrialists of the United States and Japan to frame additional questions and to initiate steps toward realizing the next generation of robots.

Introduction

Robotics has had a dramatic impact on manufacturing over the past decade. It has been the enabling technology in the widespread availability of consumer electronics, such as personal computers, video cassette recorders, and facsimile machines, and the agent of change in the transformation of the automobile industry. In both the United States and Japan, it has increased efficiency, enabled higher quality, and led to improved working conditions on the shop floor.

Looking back on the relatively short history of the world robotics industry, the 1960s appear to have been a decade of invention; the 1970s a decade of development; and the 1980s a decade of growth, stability, and maturity. U.S. firms most heavily influenced invention, Japanese firms development and growth (see Figure 1). Selective cooperation may well play a key role in strengthening robotics R&D and fostering a global marketplace in what promises to be a decade of new opportunity.

Wider and more direct impacts on people, in areas beyond the manufacturing environment, are expected from robotics in the 1990s. Cooperative efforts between the United States and Japan that might hasten advances in the application of robotics in safety, health, and personal services hold great promise not only for the participants but also, in our increasingly global economy, for the citizens of the world.

But many differences—economic and cultural—complicate the cooperation effort. Universities, government, and industry play different roles in R&D in Japan and the United States, and each country approaches planning and government/private sector cooperation differently. Moreover, the two countries' respective cultures tend to communicate in different ways. Recent studies suggest that

U.S. firms involved in international relationships, particularly with Japanese companies, often believe that they receive less than they give. It is thus important that cooperative undertakings between U.S. and Japanese firms be managed in such a way that mutual benefits are clear to both sides. Collaborative relationships should be characterized by a theme of "cooperating to learn," especially from Japan.

	1984	1985	1986	1987	1988
Australia	528	NA	800	925	1,200
Austria	116	170	250	305	446
Belgium	776	975	1,035	1,132	1,231
China-Taiwan	148	227	292	452	682
Denmark	114	164	210	277	349
Finland	180	247	336	423	545
Federal Republic of Germany	6,600	8,800	12,400	14,900	17,700
France	2,750	4,150	5,270	6,577	7,930
Hungary					89
Italy	2,000	4,000	5,000	6,600	8,300
JAPAN	**67,000**	**93,000**	**116,000**	**143,000**	**176,000**
Netherlands	213	350	630	747	845
Norway	260	323	396	431	473
Poland	NA	NA	380	410	471
Singapore	20	29	158	360	420
Spain	525	688	859	1,131	1,382
Sweden	1,746	2,046	2,383	2,750	3,042
Switzerland	191	290	382	475	783
United Kingdom	2,029	3,208	3,683	4,303	5,034
UNITED STATES OF AMERICA	13,000	20,000	25,000	29,000	33,000
USSR	NA	34,068	44,071	53,115	59,218
UNIDO Group (only Czechoslovakia)	NA	1,702	2,766	4,052	5,647

FIGURE 1 Robot population of the world. Note: Numbers exclude manual manipulators and fixed-sequence robots. NA, Not applicable. SOURCE: International Federation of Robotics.

Machines and the Manufacturing Environment

The development of general-purpose machines in Great Britain in the late 1700s precipitated a fundamental change in the way products were created. The impact of this shift from "making" to "manufacturing," though significant, was comparatively localized and was resisted in some industries. The textile industry survived labor resistance to mechanization largely because the lower prices that could be charged for products produced by machine generated more business and an attendant need for more labor. More widely felt was the innovation of interchangeable parts in the mid-1800s, which in the United States gave rise to the factory system. With the shift from general-purpose machine shop to factory, the minimum efficient scale for labor increased from 40 to 100 people. Widespread adoption of the Taylor doctrine of scientific management in the early 1900s drove the figure to 300. Development of a conveyor transport system in 1910 gave rise to mass production, which led to a 62 percent drop in the price of automobiles. A subsequent 10-fold increase in demand led to a tripling of the auto industry's labor force over the next decade.

Mechanization of manufacturing reached its zenith in the mid-1950s. Emphasis subsequently shifted to monitoring (statistical process control); controlling (numerically controlled machines); and, most recently, coordinating (computer-integrated manufacturing) production. With each of these shifts, the information load on the worker increased and the requisite technical skill requirements changed. The introduction of robots in the 1960s and 1970s, and their diffusion in the 1980s, changed the composition of indirect labor; maintenance went up and manufacturing overhead declined. (The changing role of labor in the Japanese auto industry is traced in Figure 2.) Given 100 blue collar workers today and no

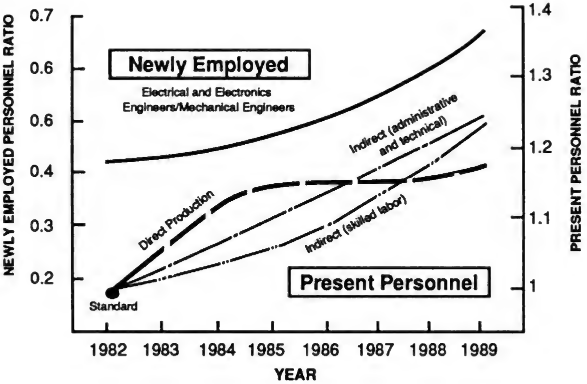

FIGURE 2 Employment trends. SOURCE: Toyota Motor Corporation.

dramatic growth in output, it is likely that in 10 years there will be 60 and in 20 years 40, of whom only 5 will be traditional blue collar workers. The remainder will be in management, process improvement, and engineering. The color of workers' collars is increasingly expected to blur.

In the United States only 20 percent of workers are currently employed in manufacturing. The Bureau of Labor Statistics predicts 15 percent by the year 2000, somewhat less dramatic a decline than that experienced in agriculture, which today employs only 3-5 percent of the labor force.

Yet the trend is clearly toward fewer and more highly skilled workers. Employment in the U.S. auto industry dropped by nearly half in the 4-year period between 1978 and 1982, leading to the development of retraining programs for displaced workers. General Motors alone has retrained some 80,000 workers since that time. Although software development in the information industry, with its 20 percent annual increase in employment, might seem a promising destination for displaced production workers, job retraining is complicated by an up to 20 percent illiteracy rate among workers in some U.S. auto plants.

The Japanese were quicker to recognize the need for anticipatory retraining and union management negotiations. Toyota's retraining programs in maintenance and repair are extended to equipment suppliers and subcontractors, as well as to indirect workers. In the United States job security in the auto industry was negotiated in 1984 and again in 1987. Jobs were guaranteed to 85 percent of the work force in return for union cooperation in increasing productivity through technological change. The impetus for this rough equivalent of lifetime employment came from the auto workers' unions, with management subsequently coming to see its value. Today, workers displaced by robots are pooled to await reassignment or retraining. Any such layoffs that occur now are market related.

Other unions have achieved less cooperation than the United Auto Workers. With a drop in the union work force from 35 percent in the mid-1950s to less than 17 percent in 1989, the role of unions in the U.S. economy is clearly declining.

Changes in the quality of labor must be managed carefully. Robotics is still an evolving technology. As the special-purpose robots that displaced unskilled production workers in heavy and dirty work are joined by flexible robots designed to accommodate production of greater varieties of products in smaller quantities, the requisite skill levels demanded of manufacturing's human work force will be pushed still higher.

Robots are no longer considered special equipment, but rather advanced forms of automated machinery. In facilitating the rapid growth of manufacturing, robotics has precipitated expansion in many tertiary industries. Increasing demand for consumer goods has necessitated expansion of distribution systems, including transportation and communication. In Japan industrial robot technology developed for primary and secondary industries is being applied in such areas as warehousing, cargo handling, and maintenance. Examples include an unattended robotics system for supermarkets and a maintenance robot for toll roads. Service industries associated with education and amusement have expanded with the rising level of consumption and increase in leisure time. Maintenance, cleaning, and repair have evolved as a new type of service industry. The technology of the so-called transport robot can be applied to the unattended transport of linens and meals in hospitals and hotels. Already in Japan there are examples of robots in customer service occupations, including a robot that takes orders and carries dishes in a restaurant and a robot that substitutes for a company receptionist.

Low productivity in service industries, and in other industries, such as construction, is directly related to the lack of automation. The urgent need for robots in these industries cannot be met with existing industrial robots, which are designed largely to substitute for dedicated machines and, to a lesser extent, for manual operations. A new generation of more flexible, intelligent robots is needed.

Three Generations of Robots

The industrial robot, its image having been widely promulgated in the print media and on television, almost invariably comes to mind today at the mention of the word robot. It has largely displaced the bipedal tin men of early science fiction.

The typically squat, one-armed, occasionally mobile first-generation robot originated in the 1960s. Usually, it was single purpose and was used in such occupations as welding, painting, and machining. Today such robots are in wide use, having matriculated through the early stages of laboratory development and technical feasibility to economic feasibility in the early 1980s.

A second generation of adaptive, sensor-based robots, at the laboratory stage in the 1970s, are just arriving at the stage of technical feasibility. These are diverse robots, with some intelligence, but still largely single function. Like first-generation robots, they are used primarily in manufacturing.

A third generation of robots is needed to work outside the factory. The industrial robots employed in manufacturing operate in highly structured environments. Often the manufacturing environment is altered to accommodate them. Altering to any great extent the environments that service robots will be called upon to operate in (e.g., undersea and construction environments, space, mines, nuclear power plants, hospitals, offices, homes) is inconceivable. To function in such unstructured environments, robots must come to resemble humans more than machines, including possession of certain humanlike faculties. Communication functions will be essential in these third-generation "intelligent" robots.

Tele-existence (often referred to as "telepresence" in the United States), a subset of third-generation robotics, aims at natural and efficient remote control of a robot by providing the operator with a real-time sensation of presence. It is an advanced form of teleoperation that utilizes rich sensory feedback to enable a human operator to function as one with a robot working in an inhospitable (e.g., highly radioactive, extremely hot, or oxygenless) remote environment. The pilot-aircraft interface in some advanced military fighter jets is a form of tele-existence.

A system for tele-existence would comprise intelligent mobile robots, their supervisory subsystems, and remote-presence and sensory augmentation subsystems that would enable the operator to derive a computer graphics-generated, pseudorealistic sensation of presence from the robots' ultrasonic, infrared, and other, otherwise invisible, sensory perceptions. Realistic visual, auditory, tactile, kinesthetic, and vibratory displays would be realized in the remote-presence subsystem. A human operator would be capable of both monitoring a robot's work through its sensors and interceding as necessary to perform the task vicariously as if conducting the work personally (ideally) or from within the robot (practically).

The principle of the display that provides a sensation of presence can perhaps most easily be understood in terms of vision. The system is based on the principle that the world we see is reconstructed by the brain using only two real-time images on the two retinas. The environment supplies to the retinas two-dimensional images that change in real time in relation to the movement of the eyes and head. We reconstruct the three-dimensional world in our brains and project it onto the real three-dimensional world. To realize a robotic display, we would have to precisely measure human movements, including those of the eyes and head, in real time; construct anthropomorphic sensors and effectors that mimic our own in function and size; ensure that they can be controlled to follow precisely the movements of a human operator; and assure that the operator sees the same visual space observed by the robot by delivering the images recorded by its sensors directly to the operator's eyes. The display must enable the operator to see the robot's upper extremities, which would be controlled to track in real time precisely the same movements as the operator.

Tele-existence has been proposed in principle, and its design procedure has been explicitly defined by the Mechanical Engineering Laboratory of the Ministry of International Trade & Industry. The laboratory has built experimental visual display hardware and demonstrated the feasibility of a visual display with the sensation of presence in psychophysical experiments. The laboratory has also constructed and evaluated a prototype mobile televehicle system, capable of being driven by means of auditory and visual sensation of presence. A visual tele-existence simulator, incorporating a pseudo-real-time, binocular, solid model robot sensor, has been developed and its feasibility has been experimentally evaluated. The feasibility of the tele-existence master-slave system also has been demonstrated. This system involves an anthropomorphic robot mechanism with an impedance-controlled active display mechanism and head-mounted display whose structural dimensions closely approximate those of humans. Economic feasibility for telepresence is perhaps 30 years in the future, but the need for it is current.

Work in telepresence is being carried out in the United States by the National

Aeronautics and Space Administration (NASA) and the U.S. Air Force, which are jointly developing a glove device capable of measuring, storing, analyzing, and displaying individual joint angles for each finger of an operator's hand and transforming these data into commands that correspond to arbitrary mechanical hand configurations. "Glovemaster" is designed to enable an operator to directly drive an analog servo system in critical applications, such as those found in nuclear power plants and space exploration. The device is accurate to three decimals and is an order of magnitude more reliable than seemingly similar devices developed for the electronic games market.

The crux of application opportunity, however, lies in autonomous robotics. Autonomy has been central to past successes and is key to future success in ever more demanding service roles. One prototype service robot in use in the United States, a successor to the 6-year-old robot developed to explore the nuclear accident at Three Mile Island, is capable of 35 motions that enable it to saw, handle, and perform water jet cutting (useful in accidents and demolition) and walk and steer over all terrains. The teleoperated robot is equipped with onboard computing and artificial vision and is capable of self-diagnosis.

Robots with long arms, robots with dual arms, and walking robots with long strides needed to operate on rugged terrain where wheels will not work are under development by NASA for space exploration. One such robot, being developed at Carnegie-Mellon University, can take steps several meters in length using legs that move through the body rather than around it. NASA is also working on semiautonomous robots capable of operating on their own for the 10 minutes it takes radio transmissions to travel between the Earth and Mars.

Land waste in the United States, estimated to be at least a $100-billion problem, has made excavation an immediate problem for robotics. Excavation robots are simple, slow, and powerful and are feasible with current technology. Eventually, intelligent robots might replace manual labor in strenuous and boring product acquisition work in farming and mining; deep-sea products, for example, might be acquired by robots transported by submersible vehicles.

Generally, outdoor applications of the robotics technology that was developed for manufacturing are limited by lack of geometry and color differentiation and the difficulty of preplanning tasks. Indoors, the problems associated with lack of structure are somewhat more amenable to less radical adaptations of advanced industrial robot technology. Toshiba, for example, is developing robotics systems for mail feeding, address block location, and irregular parcel singulation and imaging that overcome significant limitations of existing mail sorting automation, which requires that pieces be uniform in size, shape, and address location. The system incorporates feeder components, vision systems and range sensors, controllers, conveyors, and a robotic arm and vacuum gripper. For the U.S. Postal Service, which currently incurs 20 percent of its total costs in manual sorting and expects its current volume of 140 billion pieces per year to nearly double by the year 2000, the system holds great economic promise.

Intelligent robots could replace sales personnel at point-of-sale terminals at gasoline stations; fast food emporiums; and department, hardware, and grocery stores. Commonplace chores of commercial establishments, such as cleaning (of factories, warehouses, stores, hotels, and office buildings), delivery (of mail, supplies, and medicine), and security (surveillance and fire protection), could be done by personal robots. Such robots could be utilized in the home for many of the same chores as well as for cooking and retrieval.

Most of the application functions needed by personal-use robots—those that require the robot to verify, inspect, recognize, locate, grasp, transport, store and retrieve, navigate, and move (robot and end effector)—have yet to be developed. Meeting the ubiquitous requirements for reliability, speed, and low cost will entail design for automation, standardization, environment structuring, contact and noncontact sensing, artificial intelligence, human-robot communication (by speech, display, etc.), collision-damage avoidance, error recovery, and end effector design.

Surgical robots are another possibility. Though much of the technology needed for surgical robots may be borrowed from manufacturing robots, greater integration is needed. A surgical robot would be capable of analyzing a patient and simulating the procedure to be performed and of using sensing modalities to obtain feedback during an operation. Work on medical imaging systems is being done, and systems for engineering models of bones exist. Key problems in robotic surgery are man-machine interaction in the surgical situation, relating models to reality, verification, precision, operating room compatibility and sterility, safety, error recovery, and backup.

The goal of recently completed work at IBM and the University of California at Davis, for example, is precise machining of bone in cementless hip replacement surgery. The current manual procedure for preparing the femoral socket (which uses a hammer and broach) leaves gaps of 1 to 4 mm between the implant and bone, and there is very little control over where the hole is placed. In contrast, dimensional accuracies in bone on the order of 0.05 mm have been demonstrated by a robot. In these applications, the surgeon uses computed tomography (CT) images to determine where the implant is to go and does the rest of the procedure normally. Such coupling of robotic precision with human intelligence to augment surgical procedures has broad potential application in such fields as neurosurgery (where robots have already been used clinically), plastic surgery, oncology, and ophthalmology, as well as in orthopedics. Safety and man-machine communications are clearly vital factors in robotic surgery. Not only must there be many safety checks, but the surgeon must remain in complete charge at all times. He needs to know what the robot is doing at all times and be able to intervene and possibly redirect the robot interactively.

Robots with a "softer" touch, able to handle people rather than industrial machinery, could care for hospital patients and the elderly. The United States, for example, has a quadriplegic population of some 60,000, tragically augmented by 6,000 new individuals annually. Full-time care for these people, whose average postaccident life span is 45 years, is $100,000 per year. Personal robots could provide such individuals with more constant and intimate care at a lower cost than those for human attendants. The aging populations of both Japan and the United States could provide employment for vast numbers of such robots, relieving young people just starting their own families from the need to care for aging parents and aging parents from the mental burden of being cared for. Former U.S. Secretary of Health, Educations and Welfare Joseph Califano has estimated that for every month that entry of aged Americans into expensive and all too often dehumanizing nursing homes is delayed, there is a cost of $1 billion to the U.S. economy. Homes with wheelchair access will readily admit robots, and work on a "smart" house that will be more amenable to robots is under way in Japan.

A feasibility study conducted in Japan revealed the potential of, and impediments to, personal robots. Expectations were listed in the following order: household chores, security, environment, health, recreation, and education. Actual applications were prioritized as follows: home, medical services, health, sports and recreation, education and culture, human relations, public service, and shopping. Conditions for popularity of the personal robot were economy (the cost of a robot must approximate that of an automobile), friendliness, social adaptability, and ease of maintenance. Technical hurdles include safety and reliability, flexibility of operation, man-robot interface, walking or other mobility function, human safety, and energy supply.

Although U.S. committee members articulated many of the same expectations of and applications for personal robots, actual development work in the United States seems more heavily oriented toward environmental (e.g., excavation, nuclear site, space exploration) and medical services (e.g., surgery) robots than toward personal robots. It may well be economics that determine whether third-generation, intelligent robots capable of working with people in a symbiotic relationship will be used predominantly in health care and human services or in hazardous occupations, such as nuclear power plant work or undersea and space exploration.

Toward the "Third Generation" of Intelligent Robots

Although the United States played a leadership role in the development of robotics technology, U.S. manufacturers by and large failed to capitalize on this advanced form of automation. Unable to interest domestic manufacturers in their robots, pioneering firms such as Unimation licensed their technology to Japanese companies. That technology was applied broadly, beginning in the automobile plants. Robot lines were installed in parallel with manual production lines in Nissan's Okama plant, and Nissan and Kawasaki worked together to improve robotics technology. Accompanying these improvements was a vigorous emphasis on quality control.

U.S. manufacturers have lagged, and continue to lag, behind their Japanese counterparts in the adoption of robotics, in part because of their investment criteria. Whereas large U.S. firms insist on a return on investment of 15 percent, Japanese firms accept a 3 percent return on investment and often achieve greater profitability. In Japan structural relations between developers and users seem to matter more than individual company decisions. This tends to promote long-term planning and to foster a concomitant willingness to make investments that will not pay off for some time. Toshiba, for example, derives considerable support from the electric power industry and the Japanese government for much of the work it is doing in nuclear applications.

A shortage of skilled labor and a union system (industry- as well as company-wide) that promotes labor-management cooperation has enabled Japanese companies to maintain steady employment in the manufacturing sector while introducing substantial numbers of robots. Studies by MITI, Japanese labor unions, and others suggested a minimal impact of robots on employment, countering the International

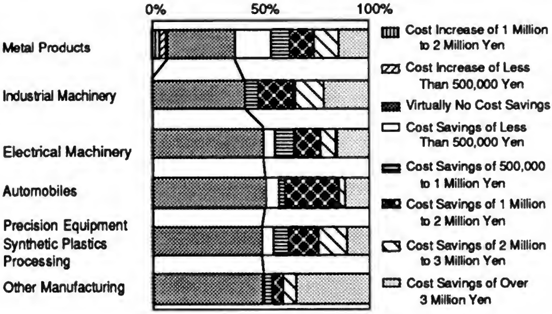

FIGURE 3 Cost savings through robotization (per robot per year). SOURCE: Japan Industrial Robot Association.

Metallurgy Federation's 1979 findings that anticipated a negative impact. Japanese labor and management reached a consensus in 1980, and discussions about the negative impacts of robotics effectively ended.

Japanese workers, being relatively secure in their jobs, more readily accept and appreciate the contribution that robots make to their firms' competitiveness. Competition is fierce among Japanese companies, and labor savings from the introduction of robots have significantly decreased the cost of production (see Figure 3). Robots have reduced the number of persons required per shift and increased the number of shifts possible (see Figure 4). In some industries cost savings from robotization have been significant.

Japanese government and industry also anticipated the need to prepare for the introduction and maintenance of robots. Recognizing the need for more workers in planning and maintenance, and for a shift from mechanical to electrical and electronic engineers, many Japanese firms adjusted their recruiting policies and placed greater emphasis on employee training. The fact that high quality is best achieved by a balance of technology and people was corroborated by a context-oriented (work organization, human resource, and management strategy) study by the Massachusetts Institute of Technology of 80 auto plants in 15 U.S. cities. The study concluded that technology was a weak predictor of productivity compared to quality and management.

By 1984 the motivation in Japan for using robots had shifted from labor cost savings and response to an aging society toward flexibility for small-lot, multi-product lines and productivity improvement. Manufacturing companies began to perceive a need to supplement simple special-purpose robots with intelligent

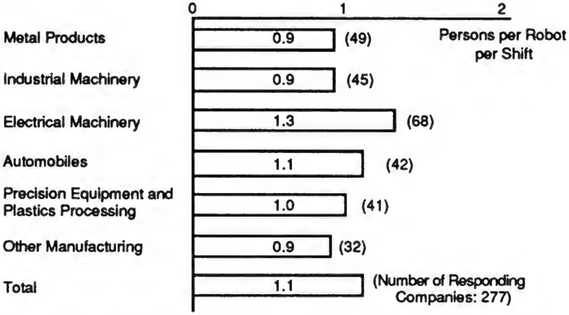

FIGURE 4 Average production worker reduction per robot per shift (per company). SOURCE: Japan Industrial Robot Association.

robots with memory and decision-making capabilities. The automobile industry, for example, came to consider increased automation of the final assembly process essential to improved vehicle performance and product competitiveness. (The shift in applications of robots in the automobile industry is illustrated in Figure 5.) Intelligent robots that corresponded to elements of the assembly process were needed. To assemble elusive matching parts in confined spaces while avoiding complex obstacles, such robots would have to be equipped with higher-level control technologies, possess visual compensation and force control, and be capable of multirobot cooperation. Improved robot arms, tools, and a more sophisticated man-machine interface would be required.

The needed R&D has been undertaken in many settings. Toshiba, a large Japanese integrated electronics manufacturer, employs 15,000 of its 70,000 employees in corporate R&D and engineering laboratories, many of which are engaged in robotics-related hardware and software development. Fifteen- to 20-year projects that would not be feasible in the United States, such as the development of certain robotics applications in the nuclear power plant industry, are undertaken by companies like Toshiba with support from the electric power industry and the government.

Although strong formal ties generally do not exist between industry and universities in Japan, informal ties are very strong. University professors typically submit research themes to the Ministry of Education in hopes of receiving small amounts of funding. Industrial funding through sponsored research and donations would be helpful, but Japanese universities have few full-time research staff members with master's or doctoral degrees and little experience coordinating large

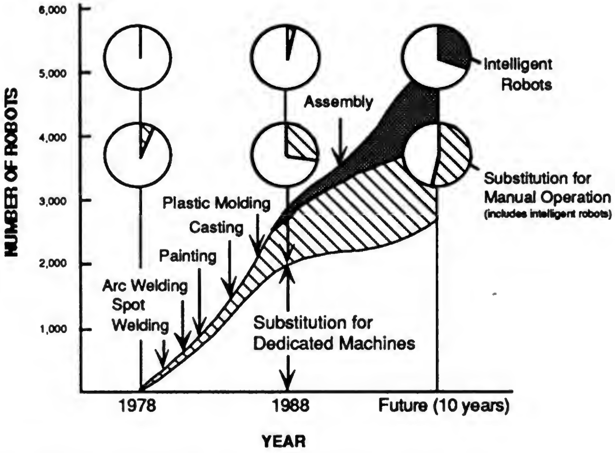

FIGURE 5 Introduction of robots. SOURCE: Toyota Motor Corporation.

R&D projects with industry. Trial organizations, such as the University of Tokyo's Research Center for Advanced Science and Technology, which was organized as a mechanism for raising industrial capital, are still in the early stages of development.

In general, industry is driving robotics R&D in Japan, with considerable support from the government. One example of Japanese government-industry cooperation is the National Research and Development Program (popularly known as the Large-Scale Project). Initiated by the Agency of Industrial Science and Technology in 1966, the program undertakes risky large-scale R&D on a commission basis under government leadership. Projects must address important and urgent needs and potentially benefit Japanese industry or society. A MITI advisory council plays a role in the selection of projects. Implementation is divided between national laboratories (which conduct basic research) and the private sector (which pursues development). Government-commissioned user associations are established in the private sector. Equipment bought by industry with government funds becomes a national asset. Project duration is typically 6 to 7 years. Ten projects are currently under way, including the Advanced Robot Technology project, which is directed at developing technologies that will provide the maneuverability and general-purpose adaptability needed to commercialize robots for inspection, maintenance, rescue, and other broadly diversified jobs, and the Automated Sewing System project, which is aimed at developing an integrated production system for small-lot production, materials handling, and sewing techniques to reduce production time for small- to medium-sized textile companies.

Three robotics projects undertaken in the United States illustrate a range of objectives, funding, and management approaches. The remote technology used for surveying and recovery at the crippled Three Mile Island nuclear reactor was developed in an applied program with specific objectives and was funded principally by the federal government. The Autonomous Land Vehicle was a government initiative that developed advanced, fundamental robot vision, planning, and navigation technology without an immediate application focus. Current NASA programs aimed at developing robotics applications for space exploration exemplify a healthy balance of basic and applied activity, focused by objective on mission scenarios, and with the latitude to build a base of progressive, future-oriented knowledge.

The National Science Foundation (NSF) has a loose strategy for funding basic research to support development of manufacturing, construction, and intelligent robotics systems and provides seed money for the dissemination of results. Needs are articulated through requests for proposals, workshops, and suggestions from study groups and other government agencies.

The National Institute of Standards and Technology (NIST) funds mainly its own activities while making small grants to universities. Needs are articulated internally by an oversight committee and externally as requests from other government agencies. NIST's R&D has had a major impact on control systems strategies.

The U.S. Department of Defense's (DOD) Joint Service Robotics Panel shares information but does not coordinate activities. Each service looks at robotics in terms of its respective mission. DOD, the largest source of funds for robotics, stimulates research through the Office of Naval Research, the Air Force Office of Scientific Research, the equivalent office of the Army, university research initiatives, and the NSF. If technical requirements of DOD's service requests call for developing enabling technologies, the work is routed to the Defense Advanced Research Projects Agency.

In addition, the departments of Energy (DOE), Health and Human Services (HHS), and Interior (DOI) are all engaged in robotics research. DOE research focuses on nuclear and hazardous waste, HHS on applications for the handicapped and in prosthetics, and DOI on mining and undersea applications. In all three agencies, management identifies needs, which are evaluated internally.

Most industry-university cooperation in the United States involves industry funding of university-based projects. Resources and research needs may not coincide in university settings. Institutions such as Carnegie-Mellon University, which has a strong robotics program, must compete for resources. Unmanned excavation, for example, though perceived as a need at Carnegie-Mellon 4 years ago, was not funded. Eventual funding by the NSF was insufficient to support the initiative.

The United States hosts mainly basic research on dynamic control, machine perception, artificial intelligence, and neural networks. Funding is largely from the federal government, with development carried out at open universities. Because the U.S. government funds comparatively little applied research in robotics, and only defense programs fund development in industry, transfer of the universities' basic research into products has been slow. In Japan robotics research is largely applied, and there is more cooperation among government, industry, and academe. Programs include undersea, construction, and health care robots. Japanese researchers benefit from attendance at those U.S. universities where basic research is carried out, but there is no mechanism by which U.S. companies can benefit from applied research conducted in Japan. These differences in how robotics technology is developed and commercialized in the United States and Japan—differences in the focus of research, sources of funding, and mechanisms for technology transfer—can be viewed as a platform for cooperation.

The United States and Japan do not have a history of successful cooperation in the development of robotics technology. U.S. technology has gone to Japan via licensing. Japanese companies have insisted on manufacturing licenses while refusing to distribute U.S.-made products. Many U.S. companies believe that Japanese robotics companies are reluctant to license their technology to U.S. companies for manufacture. Past proposals for collaborative efforts have generated skepticism among U.S. partners, even though they could theoretically learn from Japanese companies about how to manage cooperation. Future efforts must, therefore, demonstrate clear benefits to both sides. Because of these factors, many believe that cooperative work can best begin in noncompetitive areas where there are no likely immediate commercial impacts but where the goals are clearly defined and attainable within a few years.

Unless the two major players in this arena learn to cooperate, the world is not likely to benefit any time soon from the capabilities of disaster recovery robots and personal robots or the care of the elderly and infirm.

U.S.-Japan Cooperation: To What End? On What Basis? In What Areas?

Four purposes of U.S.-Japan collaboration in robotics are readily identifiable. Two are technical objectives—to address gaps in the science base and to develop needed technologies. The United States is better at the former, Japan at the latter. Another purpose is to learn to collaborate. Historical competitive patterns, together with legal restrictions, have produced few examples of formal R&D collaboration among U.S. companies and little experience with international cooperation involving groups of firms. U.S. companies need to learn to collaborate, and cooperative programs in robotics R&D could provide a test case upon which cooperative efforts in other areas might build. Finally, U.S.-Japanese cooperation in robotics would serve to familiarize the two countries with one another's R&D infrastructures.

The relative strengths of these prospective partners have been articulated already. Basic research is the forte of the United States, while applied technology is Japan's. The approach taken in Japan has been to create structure and organizations first and think about the "heart" of a project later. U.S. firms often confuse technology and business. Technology cannot do business by itself; U.S. firms should recognize production engineering as technology. Combining and integrating these strengths and characteristics can make both countries more significant players in the international community.

It may well be that cooperation through existing modes would further the Japanese approach. Cooperation must be structured in such a way that U.S. partners learn about the process through which technological applications are realized in Japan. Successful U.S.-Japanese cooperation will be rooted in areas that yield mutual benefit. Potential collaborative efforts should be achievable in a relatively short period of time—2 to 3 years—and should show concrete, but not immediately commercializable, outputs. Preference should be accorded projects that no one company or university would consider funding on its own.

Mechanisms for international collaboration can be based in the public sector (e.g., MITI, NSF, NASA) or the private sector (company to company). One U.S. company representative suggested that Japanese robot users fund technical development by U.S. companies, perhaps in exchange for joint manufacturing rights rather than just licenses. To allay concerns that they might just establish subsidiaries in the United States, they might license technology to U.S. firms and agree to distribute, rather than just license, U.S. products. The same individual also suggested that the Japanese government expand economic incentives to help U.S. companies establish subsidiaries in Japan. Another suggestion was that the U.S. government improve mechanisms for the collection of information about new technological developments in Japan (e.g., new experiments by users and activities at particular R&D centers) and make it quickly and broadly available to U.S. companies.

We are not without models of U.S.-Japanese cooperation. GMFanuc Robotics Corporation, a U.S.-based company established by General Motors and Fanuc Ltd., is an equally owned joint venture created to produce and distribute robots and optimized robotic production systems that will increase the competitiveness of its customers. The business objectives of both parent companies are served by having equal representation in GMFanuc's policy management. Japanese strengths in market orientation (e.g., Japanese appreciation for mechanical constraints on robots) are expected to foster a production orientation in a development environment that synergizes philosophical differences in behavior between U.S. and Japanese engineers. Cross-licensing agreements are intended to promote technology transfer between the two parents. The degree of success achieved by these approaches and policies will be revealed in time.

Given the mechanisms, criteria, and impetus for collaboration, U.S. and Japanese companies need to find suitable areas for cultivation. There are two ways to find such areas: (1) identify an area in which both countries already have considerable, potentially complementary, technology and marry these technologies in one project and (2) choose an area to which each can bring a strong basic skill but in which neither has much expertise. Nuclear emergency and disaster response robots are examples of the former. Both U.S. and Japanese policymakers are interested in such technologies in light of events at Chernobyl and Three Mile Island, but work on radiation-hardened electronics and autonomous locomotion in human-scale spaces is in its infancy. Health care is an example of the latter area. Japanese work on health care robots has focused on patient service and clinical practice, whereas U.S. work has focused on robotic surgery.

The realization of third-generation robots presupposes a host of fundamental developments. An analogy might be drawn to the introduction of the automobile. Besides developments required to make motor vehicles a practical reality, a suitable environment (roads and rules) had to be created. Similarly, an environment must be created that is conducive to the coexistence of intelligent service robots and humans. Key components and generic technologies need to be developed. Advances in very large scale integration (VLSI), sensor technology, and machine vision will be required. Goals should be set high. In scope, this foundation-laying work might be likened to putting a man on the moon. Neither the United States nor Japan has efforts in all important areas, and, individually, both may lack the resources to do it all and do it well in a timely fashion. This is a convincing rationale for expending considerable effort on cooperation in a few selected areas.

Robotics has passed from a labor substitution technology to one that increasingly complements human labor. In manufacturing emphasis is shifting from labor savings to labor enhancement. Beyond manufacturing, a host of service robot technologies directed at the underlying goal of all technology—improving the amenity of life—is foreseen. We are looking forward to the potential of robots used in hospitals and in the care of the elderly and infirm, in construction, waste disposal, and nuclear power plant and other hazardous work and even as personal attendants and companions in the home. Applications of robotics in space, an area where both the United States and Japan have made significant investments, is another potential area for collaboration.*

The necessary collaboration, like the achievements, will not come easily. Fundamental differences in U.S. and Japanese cultures, societal structures, and emphasis and orientation must be overcome or effectively synergized. Criteria for arriving at projects that can accomplish this have been identified:

- ensure mutual benefit;
- exploit complementary capabilities (resources, information); and
- embark on realistic projects that will yield measurable, but not immediately commercializable, results in a relatively short (2- to 3-year) time frame.

Specific areas suggested during the exchange were joint work on service robots and robots to work in hazardous environments, as well as joint study of the socioeconomic impacts of such robots, perhaps including joint curriculum development for training a new generation of workers to function compatibly with a new generation of intelligent robots. Achievements of U.S.-Japanese collaboration in robotics in such areas as protection of the Earth's environments, medical treatment, and enhancement of human welfare will become common properties of all mankind, to the considerable credit of both countries.

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* See National Research Council, *Space Technology to Meet Future Needs*, National Academy Press, 1987, for an analysis of the special considerations that must be taken into account in applying robotics technologies to space exploration. Themes that might be explored for collaborative research include telepresence, cooperation between manipulators and robots, trainable systems, sensing, and perception.

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